Capacitance

by Larry R. Luchi W7KZE

[Editor's Note: This technical discussion of capacitance is a bit more advanced than what we usually publish in Radio Fun, *and it may leave some of you in the dark. If so, read it through a few times—slowly—and things should begin to sink in. If you want to get the most out of amateur radio, you've got to really understand this stuff—not just memorize a bunch of answers for a test.*

We've asked Mr. Luchi to prepare a series of articles focusing on various electronic components and their properties. We'll publish them from time to time, and if you stick with them, you'll be well on your way to a solid foundation in electronics.—David N1GPH]

The General, Advanced and Extra amateur radio exams all have common questions from a pool on the subject of "Capacitors and Capacitance." This article is for those hearty amateurs who are on the road to upgrade.

A capacitor consists of an insulator (called a dielectric) between two conductors. The conductors make it possible to apply voltage across the insulator. Different types of capacitors are manufactured for specific values of *C* (symbol for capacitance). They are named according to the dielectric. Common types of dielectrics are: air, ceramic, mica, paper, plastic, and electrolytic. Capacitors used in electronic circuits are small and economical. The most important property of an ideal capacitor is to block DC current and pass AC current. The higher the AC frequency, the less opposition for AC voltage or current.

Capacitors are a common source of trouble because they can have either an open circuit or a short circuit through the dielectric. Electrolytic capacitors that are physically located near heat-radiating devices tend to dry up, thereby causing a short circuit. This article describes these problems, and includes the method of checking a capacitor with a digital ohmmeter, even though a capacitor is actually an insulator.

Capacitance

What is a dielectric? A nonconducting material that does not pass DC electric current. It is possible for dielectric materials such as air or paper to hold an electric charge because free electrons cannot flow through an insulator. The electric field distorts the molecular structure so that the dielectric is no longer neutral. The dielectric is actually stressed by the invisible force of the electric field. As evidence, the dielectric can be ruptured by a very intense field with high voltage applied across the capacitor.

The factors that determine the capacitance are the area of the plates exposed to each other, and the composition of the nonconducting material between the plates. Two plates, each with an area of $1"^2$ when separated by 0.001" of air, produce a capacitance of 225 pF. If each plate area is doubled (spacing remaining 0.001"), the capacitance doubles to 440 pF. Capacitance is directly proportional to the area of the plates.

If the spacing of the two $1"^2$ plates is increased to 0.002", the path of the electrostatic lines of force between the negative plate and the positive plate is twice as great, resulting in only half as intense an electrostatic field and only half as much capacitance. Capacitance is inversely proportional to the space between plates.

The nonconducting *dielectric* material determines the concentration of electrostatic lines of force. If the dielectric is air, a certain number of lines of force will be set up for a given applied voltage. Other materials offer less opposition to the formation of electrostatic lines of force. For example, with one type of paper instead of air, the number of electrostatic lines of force between the plates may be twice as great. Such a capacitor will have twice as much capacitance, and will have twice as many electrons flowing into and out of it with the same applied source voltage. The paper is said to have a *dielectric constant*, or *specific inductive capacity*, twice that of air. Capacitance of a capacitor is directly proportional to the dielectric constant. The approximate dielectric constant, or specific inductive capacity, of some common dielectric materials is given in Table 1.

The dielectric constant of solid dielectric materials may decrease with an increase in frequency. The molecules of the dielectric do not have sufficient time to conform to the rapidly changing electrostatic lines of force that they must support. If the lines of force cannot be fully developed in the dielectric molecules, the dielectric constant and the capacitance will be less. Therefore, a 0.1 µF paper capacitor may have 0.1 µF at 1 MHz but will have considerably less at 100 MHz.

Charging a Capacitor

These are the two main effects with capacitors. Applied voltage puts charge in the capacitor. The accumulation of charge results in a buildup of potential difference across the capacitor plates. When the capacitor voltage equals the applied voltage there is no more charging. The charge remains in the capacitor, with or without the applied voltage connected. This is illustrated in Figure 1.

Discharging a Capacitor

The capacitor discharges when a conducting path is provided across the plates, without any applied voltage. Actually, it is only necessary that the capacitor voltage be more than the applied voltage. Then the capacitor can serve as a voltage source, temporarily, to produce discharge current in the discharge path. The capacitor discharge continues until the capacitor voltage drops to zero or is equal to the applied voltage.

Dielectric Losses

Almost all the energy stored in the electrostatic field of a capacitor is converted into some other form of energy when the capacitor is discharged. However, two losses occur in the dielectric itself.

Electrons on the negative plate of a charged capacitor may find a high-resistance path to the positive plate through the dielectric, forming a leakage current to the other plate.

Another kind of dielectric loss is indicated by heat in the capacitor. It is caused by the friction of the molecules of the dielectric material as they are changed from one strained position to the opposite by any reversing of the electrostatic lines of force. This process is called hysteresis, and it is normally significant only when an alternating current produces rapid charging and discharging of the capacitor. It increases as the frequency of the AC increases. For this reason, many capacitors operate satisfactorily at lower, but not at very high, frequencies.

The Farad Unit of Capacitance

With more charging voltage, the electric field is stronger and more charge is stored in the dielectric. Figure 2 shows that the amount of charge stored in the electric field is proportional to the applied voltage. Also, a larger capacitance can store more charge. These relations are summarized by the formula:

$$Q = CV$$

where Q = charge, in coulombs
C = capacitance, in farads
V = voltage, in volts

The C is the physical constant, indicating the capacitance in terms of how much is stored in the dielectric with a potential difference of one volt, the capacitance is one *farad*.

Practical capacitors have sizes in millionths of a farad, or smaller. The reason is that typical capacitors store charges of microcoulombs or less. Therefore, the common units are:

1 microfarad = 1 µF = 1×10^{-6} F

1 picofarad = 1 pF = 1×10^{-12} F

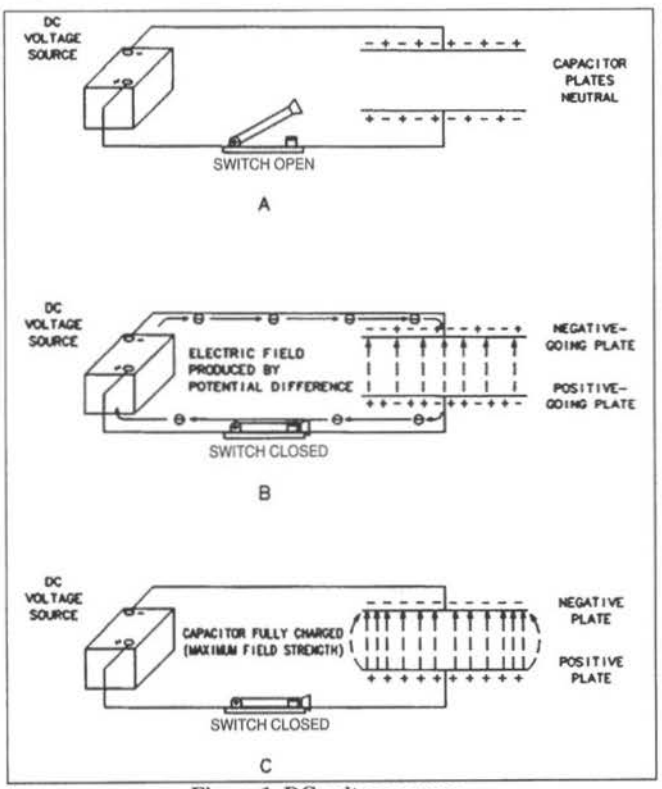

Figure 1. DC voltage source.

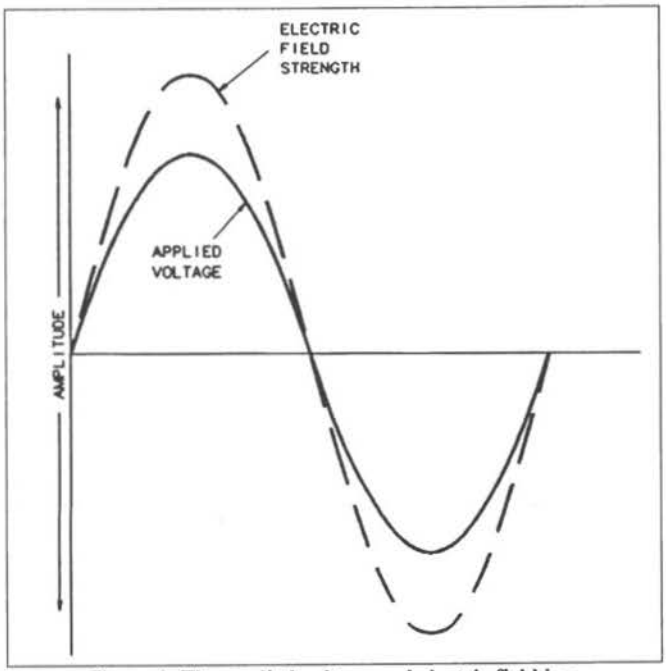

Figure 2. The applied voltage and electric field in a charged capacitor are in phase.

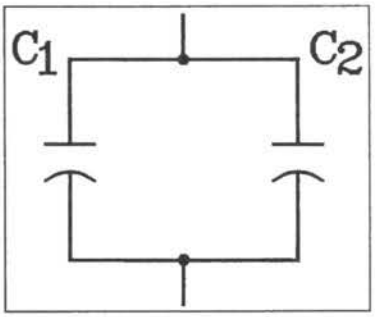

Figure 3. Capacitors in parallel.

Table 1. Dielectric Constants

Material	Dielectric Constant
Vacuum	1
Air	1.0006
Rubber	2-3
Paper	2-3
Ceramic	3-7
Glass	4-7
Quartz	4
Mica	5-7
Porcelain	6-7
Water	80
Plastic film	2-3
Tantalum oxide	25
Barium titanate	7500

Types of Polarized Capacitors

Polarized capacitors are *electrolytic capacitors*. There are two major types of electrolytic capacitors: aluminum and tantalum.

The essential parts of an *aluminum electrolytic capacitor* are the aluminum plates and the dielectric *aluminum oxide*. The electrolyte, which is a conductor, is a chemical compound or mixture in either a dry or a paste form. The separator is made from porous paper or gauze which is easily penetrated and saturated by the electrolyte. The composition of the electrolyte varies, depending on the desired capacitor characteristics and rating, but is usually quite alkaline.

The electrolyte aids in electrochemically forming and maintaining the aluminum oxide on the positive plate *when the plate is positive with respect to the electrolyte*. If the polarity is reversed, the electrochemical reaction reverses and a large current flows through the capacitor as the oxide is removed. This large current heats the electrolyte and destroys, often with a violent explosion, the capacitor. Therefore, the polarity of the electrolyte must be observed.

The two aluminum plates of the electrolytic capacitor are long narrow strips of aluminum foil which are alternately stacked with two strips of electrolyte-saturated separation material. The positive plate has an oxide layer on *both* surfaces. If it did not, the electrolyte would short the unoxidized surface of the positive plate to the negative plate.

One characteristic of all rolled (tubular-shaped) capacitor elements should be noted: Rolling almost doubles the effective plate area. This is because, except for the last turn of the outside foil, both surfaces of the foil are utilized.

A *tantalum electrolytic capacitor* is different. Instead of the rolled foil construction, the tantalum capacitor has a tantalum slug or pellet for its positive plate (or anode, as it is often called for a tantalum capacitor). This slug is covered by a very thin layer of *tantalum pentoxide*, which is the dielectric. Because tantalum pentoxide has a higher dielectric constant than does aluminum oxide, the tantalum electrolytic has a higher capacitance-to-volume ratio than does the aluminum electrolytic.

The electrolyte, in either the solid dry form or the wet gel form, surrounds the pentoxide layer. Finally, the electrolyte is encased by the negative plate (or cathode as it is often called) which is often made of a thin layer of silver lined with a thin layer of graphite. The capacitor element is then encapsulated in an epoxy coating or in a metal case.

Parallel Capacitances

Connecting capacitances in parallel is equivalent to adding the plate areas. Therefore, the total capacitance is the sum of the individual capacitances, as shown in Figure 3.

A 10 µF capacitor in parallel with a 5 µF capacitor, for example, provides a 15 µF capacitance for the parallel combination. The voltage is the same across the parallel capacitors. **Remember that adding parallel capacitances is opposite to the case of inductances in parallel and resistances in parallel.**

Series Capacitances

Connecting capacitances in series is equivalent to increasing the thickness of the dielectric. Therefore, the combined capacitance is less than the smallest individual value. Series capacitance is calculated by the reciprocal formula:

$$C_t = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{\quad} + \ldots \text{etc.}}$$

Any of the short-cut calculations for the reciprocal formula apply. For example, the combined capacitance of two equal capacitances of 10 µF in series is 5 µF. That is, if all capacitors are of equal value you divide the value by the number of capacitors.

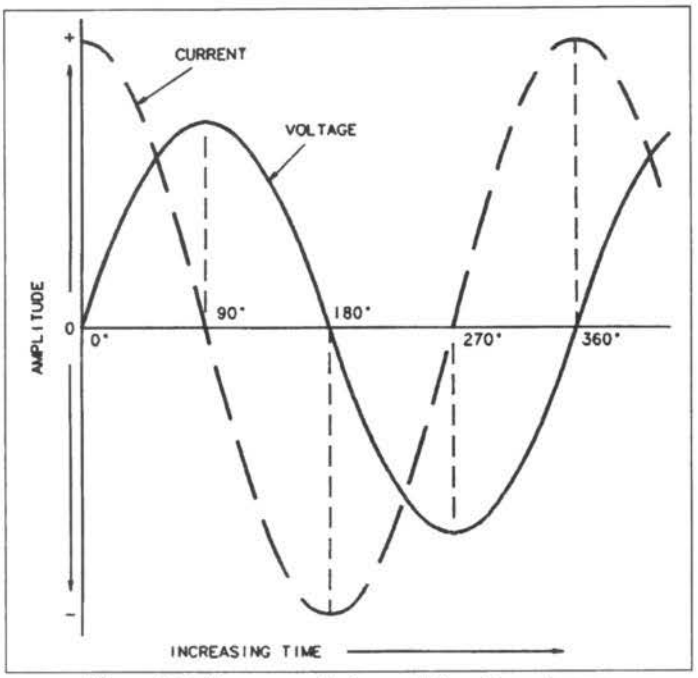

Figure 4. Voltage-current phase relationships when an AC voltage is applied to a capacitor.

Phase Angle Between Current and Voltage

The current in an ideal-capacitor circuit reaches its peak value when the voltage is zero. (An ideal capacitor is one which has a dissipation factor of zero.) As shown in Figure 4, this causes the current to be exactly 90 degrees out of phase with the voltage. Notice that the *current leads the voltage* by 90 degrees because the current reaches its + peak before the voltage reaches its + peak.

Troubles in Capacitors

Capacitors can become open or short-circuited. In either case, the capacitor is useless because it cannot store a charge. A leaky capacitor is equivalent to a partial short circuit where the dielectric gradually loses its insulating properties under the stress of applied voltage, lowering its resistance. A good capacitor has very high resistance on the order of megohms; a short-circuited capacitor has zero ohms resistance, or continuity; the resistance of a leaky capacitor is lower than normal.

Checking Capacitors with an Ohmmeter

If an ohmmeter reading immediately goes almost to zero and stays there, the capacitor is short-circuited. Using a digital multimeter, the display will show 0000 or 0002.

If the capacitor shows charging, but the final resistance reading is appreciably less than normal, the capacitor is leaky. Such capacitors are particularly troublesome in high-resistance circuits. When checking the electrolytic, reverse the ohmmeter leads and take the higher of the two readings.

If the capacitor shows no charging action but just reads very high resistance, it may be open. Some precautions must be remembered, however, since very high resistance is a normal condition for capacitors. Reverse the ohmmeter leads to discharge the capacitor, and check it again. Remember that capacitance values of 100 pF or less normally have very little discharging current for the low battery voltage of the ohmmeter. RF

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